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Design and implementation of a 100 kVA transformer monitoring and fault detection system for distribution network

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Abstract

The increasing complexity of today's power distribution networks requires reliable and intelligent monitoring and maintenance systems, especially as the demand for electricity increases due to technological and population growth. Transformers, as critical infrastructure components, are susceptible to faults such as overloads, phase losses and neutral failures. These faults can result in service interruptions, high maintenance costs and reduced power quality. Despite the various approaches that have been explored in the literature, existing systems often lack phase-specific fault detection, real-time reporting, and effective integration with communication technologies. This paper presents the design and implementation of a 100 kVA distribution transformer monitoring and fault detection system using IoT and GSM technologies. The system features advanced sensors, local and remote data logging, and immediate fault reporting via SMS, real-time data acquisition and an IoT platform (ThingSpeak). It addresses specific limitations of current systems. These include the inability to confirm transformer energization status during fault events. The test results validate the accuracy and reliability of the system and demonstrate its effectiveness in improving the life of transformers, reducing downtime and enabling predictive maintenance. The accuracy of the system is demonstrated by a Pearson correlation coefficient of > 0.96 when compared to traditional instruments (multimeters). The solution is affordable, scalable and in line with the digital transformation of the electrical infrastructure, which makes it particularly suitable for use in developing countries' power grids.

Keywords: Distribution transformer, Monitoring system, Fault detection, Fault reporting, Microcontroller, ThingSpeak IoT platform

Introduction

To ensure that the electrification demands of households for energy, water and food to meet a substantial portion of energy is needed for the electricity requirements to directly support the three sustainable development goals (SDGs): SDG2, SDG7, SDG13, and indirectly other SDGs [1–4]. Unfortunately, world energy demand is rising to the detriment of the environment around us [5]. The ecology, health, economic status, and general well-being of society are directly affected by the exploitation of high-emission energy sources. Access to clean, safe, secure, and reasonably priced energy is a key indicator of

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quality of life, as energy has become essential to daily existence [6, 7]. The increasing demand for electricity due to technological advancements and population growth has resulted in overloaded grids and transformers [8, 9]. Transformers are static electrical devices, transfer electrical energy between two or more circuits, either stepping up or stepping down the voltage as needed [10]. Using the principle of electromagnetic induction, a transformer can be described as an electrical device used in an electrical power system to transfer power between different circuits [11]. Fundamental magnetic fields are used to transfer energy from one circuit to another. The flow of an electric current in a conductor causes the induction of a magnetic field around that particular conductor. Voltage induction takes place in the second conductor when another conductor is brought into action of the first so that they are connected [12]. Transformers are crucial components of the domestic and international electricity infrastructure, often described as the heart of the power system [13], with an average life up to 20–35 years; they can exceed this lifespan if properly maintained and operated under ideal conditions [14, 15]. The majority of these components have been operating for many years under a variety of conditions such as electrical, environmental, and mechanical circumstances [16]. Figure 1 shows the schematic of a 100 kVA distribution transformer [17].

Power systems engineer must incorporate safety measures into their design to alert to any potentially harmful occurrences that the system may encounter at any moment. The operation of distribution transformers within rated conditions (as specified on their nameplate) ensures their extended service life [18]. Therefore, Proper design and construction, along with regular monitoring, make transformers reliable [19]. However, factors like overloads, overheating, and high or low voltage/current can significantly shorten their lifespan, leading to unexpected breakdowns and impacting the economy [20, 21]. When transformers fail, the consequences include increased costs, reduced reliability and efficiency, and compromised quality of electricity supply [22].

To ensure the reliability and efficiency of the electrical distribution network, it is essential to develop a real-time remote monitoring system for transformers. This system will help detect faults such as blown fuses, low-voltage supply, transformer neutral failure, imbalanced loading, and overload, thereby reducing the risk of damage

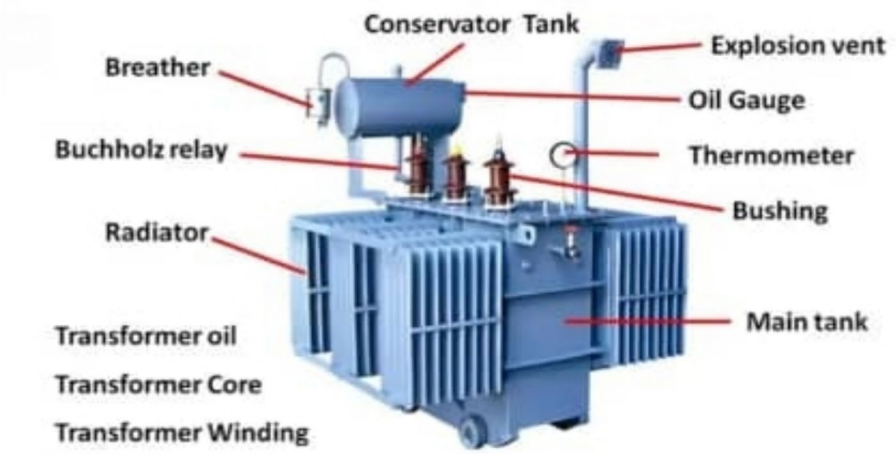

Fig. 1 100 kVA distribution transformer

and improving the quality of power supply. In emergencies, remote monitoring technology enables real-time decision-making and reduces the need for human presence on-site. This allows transformers to be managed and supervised anywhere, and at anytime [23]. This study addresses the need for an efficient and reliable system for monitoring and detecting faults in distribution transformers. Current challenges include Overloading, overheating, and other electrical faults that can lead to significant power outages, and delayed fault detection, resulting in increased downtime, higher maintenance costs, and customer dissatisfaction due to the slow response of power utilities [24, 25]. There is a pressing need for a remote monitoring and fault detection system that can intelligently monitor transformers, detect faults in real-time, and enable proactive maintenance. The significance of this project extends to both utility companies and electricity consumers. The system will optimize resource use for utility operators by replacing labor-intensive manual monitoring with an automated solution, thereby reducing maintenance delays and mitigating legal risks associated with negligence. Conversely, consumers will benefit from fewer outages, better equipment protection, and a more reliable electricity supply. This research underscores the necessity of integrating advanced monitoring technologies into power infrastructure to meet the demands of a modern, rapidly evolving world.

According to research, the efficiency and quality of electricity distributed to customers via the distribution network are primarily determined by the network's intelligent character and efficient performance. Many researchers have studied performance enhancement in distribution transformers through system monitoring, including sensor-based tracking of key power distribution variables.

Kumbhar and Patil, [26] designed a transformer monitoring system using PLC, relays and sensors to detect transformer faults such as overload, overvoltage, undervoltage, phase-to-phase faults and over-temperature faults. Since the probability of faults on distribution transformers is undoubtedly higher, the protection of the transformer is highly essential. The implementation of the system achieved a good result, as the circuit was able to shut down the transformer permanently when a fault is detected. However, the system failed to switch the transformer back on when the fault is rectified, and it lacks the knowledge to inform the relevant authorities about the abnormality and give its location, which means the transformer can be out of service for several hours, leading to a breakdown in economic growth and poor reliability. In another research Tosin et al. [27] designed a monitoring system capable of continuously monitoring the temperature of the transformer, predicting the occurrence of overheat and overcurrent faults and transmitting the fault diagnosis to the base station via a GSM modem. This allows corrective action to be taken as soon as an anomaly is detected, helping to avoid catastrophic failures. Similarly, Okeke, and Ehikhamenle [28] designed a system to solve complex problems and eradicate them using local protection techniques such as fuse and circuit breakers. The research uses a microcontroller for transformer monitoring with real-time data logging capabilities to monitor transformer parameters like voltage, current, and temperature. As the load current exceeds the rated current rating of the transformer, the temperature of the secondary winding rises, the microcontroller send an SMS through the GSM modem to the control room, informing them of the transformer overload faults.

Subha et al., [29] carry out a real-time monitoring device for a distribution transformer by using an IoT-based system to monitor load currents, voltages, ambient temperature and humidity. The device measured and processed the load current, the voltage, the temperature and the humidity of the transformer and recorded them in the memory of the system on every-minute basis and communicate the data to the user to identify the problems before a catastrophic failure occurs. Similarly, Hanafi [19], developed an IoT system for transformer current, noise and temperature monitoring and performance evaluation. The monitoring system makes use of three types of sensors to detect current, sound and temperature. The results show that the IoT health monitoring system is acceptable as it reduces errors and saves time in measuring parameters. The manual approach is another method of transformer monitoring. In the past, the maintenance team always visited the transformer site to manually measure the oil level, float level, temperature level and overload. This was a very tedious and inefficient way of monitoring the transformer. Other novel methods used for monitoring transformer are presented in [30–32].

Varieties of research on transformer monitoring and fault detection systems for distribution networks using IoT have been carried out. However, significant gaps have been identified in their existing methodologies. Firstly, there is a lack of designs that monitor and report when distribution transformers are tripped due to a fault, even though their service feeder is still active. Secondly, current systems that monitor and report lost transformer phases or blown low-voltage fuses do not confirm that the transformer is still energizing before a lost phase or blown fuse text message is sent to the distribution system operator, especially when all three fuses are involved. Thirdly, traditional instruments like the multimeter have long been used to measure the current and voltage parameters. However, the limited correlation studies between IoT-based monitoring devices and conventional instruments highlight the need to establish and validate the correlation for IoT-based monitoring approaches. These gaps indicate the need for further research and development to implement GSM-based reporting for transformer trip events, neutral failures, low-voltage supply, and blown fuse fault conditions. This research work is based mainly on the low-voltage (LV) three phase step-down distribution transformers such as transformers with ratings of 11/0.38 kV, 33/0.38 kV.

By addressing specific gaps, this research contributes significantly to

1. The proposed solution will help operators identify less loaded phases when adding new loads to the transformer, gather maximum real-time information about a transformer's operating conditions, and extend the life of transformers through timely problem recognition and remediation.
2. By using IoT to visualize remote data, the proposed system improves operational visibility and facilitates data-driven decision-making. In addition, this study emphasizes the significance of incorporating monitoring systems with IoT platforms, thereby bridging the gap between traditional practices and modern smart grid applications.
3. These innovative solutions contribute to the advancement of electrical engineering knowledge, especially in developing nations where outdated systems still dominate. As a whole, this research provides a cost-effective and scalable solution in line with the global trend of digital transformation of power systems.

This study is structured into five sections. Sect. "Introduction" contains an introductory section on transformer monitoring along with related work. Sect. "Materials and methods" describes the proposed monitoring system design, Fault detection algorithm and the experimental setup. Sect. "Results and discussion" present the result and discussions. The paper then concludes in Sect. "Conclusion" with a series of recommendations regarding transformer monitoring and faults detection.

Materials and methods

The system design

Monitoring transformers manually involves checking equipment regularly, which takes time and can be prone to error. Automatic monitoring using Arduino is more efficient and reliable. It uses sensors to identify problems quickly and maintain detailed records, improving transformer management. The methodology optimizes distribution network operations by using real-time data on transformer performance. Sensor modules such as current and voltage divider sensors measure distribution transformer phase voltage and line current. A data logger with an integrated circuit multiplexer expands the analog input capacity of the Arduino Mega board. Sensors measure and send data to Arduino Mega, the data are stored on an SD card and displayed on an LCD. A real-time clock provides accurate timekeeping. An ESP32 module provides internet connectivity and sends data to the ThingSpeak cloud for remote monitoring. Fritzing software is used to develop a schematic for the monitoring system. All sensors are connected to the Arduino Mega microcontroller. The system detects transformer tripping, neutral failure, undervoltage, and blown fuses through a detection and signaling circuit. The signals are processed by the microcontroller, which sends alerts to the maintenance or technical operations team. A digital display showing the parameter values of the substation and notification of the transformer fault to a mobile phone provides real-time monitoring. This method ensures continuous monitoring, accurate reporting, and timely intervention, thereby increasing the reliability of the distribution network. The block diagram in Fig. 2 shows the flow of a transformer monitoring and failure detection system for a distribution system.

Components descriptions

Figure 3 shows the materials of the measuring system.

i. **Arduino mega Microcontroller:** The microcontroller is a simple chip, which is programmable and used for control-oriented instructions. Arduino mega features 54 digital I/Os, 12 analog inputs using a 16MHz crystal between pins A0-A12, TTL serial communication, SPI and I2C. Arduino Mega serves as the central hub for monitoring crucial parameters such as voltage, current, and power, from the secondary site of the transformer. The microcontroller also handles the electrical faults, communication with the GSM modem and LCD unit to send SMS notifications and display overvoltage warnings. The Arduino mega microcontroller is chosen due to the higher number of I/O pins.
ii. **PZEM-`004t sensor:** The PZEM-004t module is a multi-functional AC sensor module that has the following functions for the measurement of power, voltage,

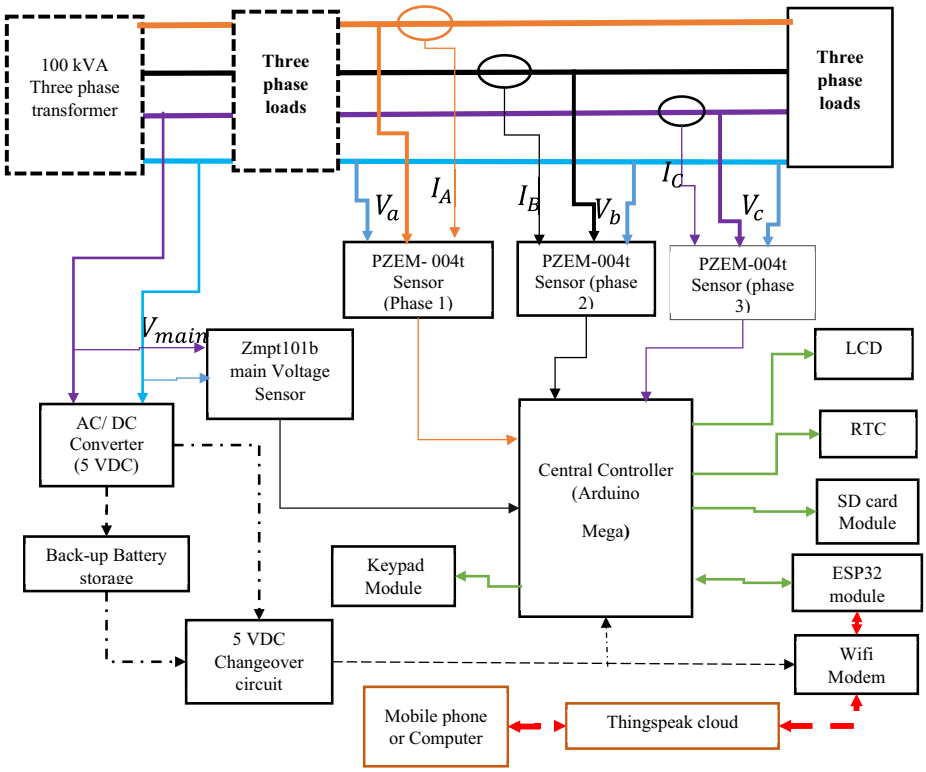

Fig. 2 Block diagram of distribution transformer remote monitoring and faults detection system

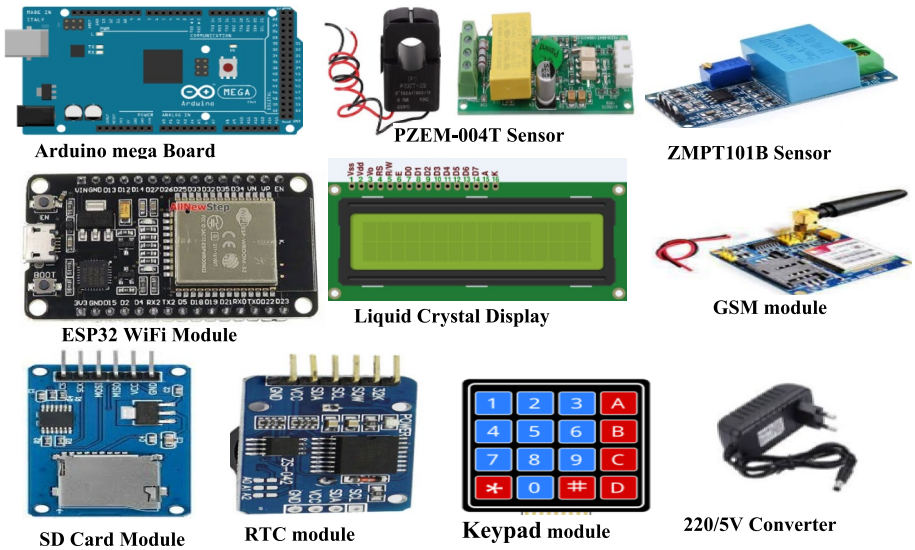

Fig. 3 Major materials for the system

current, power factor, frequency and energy contained in an electrical current. This module is equipped with an integrated voltage and current sensor (CT). It is specifically designed for indoor applications and the installed load must not exceed

the specified capacity. The sensor choices is due to high accuracy ± 0.5% and its multipurpose measurement ability.

iii. **ZMPT101B Voltage Sensor:** The ZMPT101B is a voltage sensor module. It is designed to measure AC voltages. It is commonly used in applications for the monitoring and measurement of the voltage levels in AC system. The module provides an isolated measurement of the AC voltage using a built-in transformer and voltage divider circuit. The ZMPT101B voltage sensor module is typically operated from a supply voltage of 5V and is capable of measuring AC voltages in the range of 0 to 250V.

iv. **ESP32-based controller:** NodeMCU featured firmware and hardware built around the ESP-12 module, making it a low-cost, open-source IoT platform. As arduino.cc started to develop other MCU boards based on non-AVR microprocessors, they upgraded the Arduino IDE to support a variety of toolchains, such as the arm/sam MCU. The Arduino IDE's esp32 core has emerged as a popular platform for development boards, notably NodeMCUs.

v. **The Liquid Crystal Display:** LCD is a display technology commonly used in electronic devices, including Arduino projects. An LCD comprises a liquid crystal material between two layers of glass or plastic [33]. The liquid crystals are electrically activated to either let light through or block it out, resulting in the creation of images or text on the display. LCDs are popular for Arduino projects because of their low power consumption, ease of connection, and flexibility in displaying information.

vi. **vi. GSM module:** GSM is a digital cellular system for use by mobile devices. They are an international standard for mobile communications, which is commonly used for long distance communications. Users can send and receive data, send and receive SMS, and make and receive phone calls via GPRS using the SIM900A module. The GSM/GPRS unit interacts with the microcontroller or PC terminal via USART. GSM module is use to sends a predefined message to the utility operator to inform them of the transformer's disconnection, circuit breaker trip, fuse blown, and an overvoltage is supplied due to a neutral failure.

vii. **vii. SD Card Module:** The SD card reader is a serial peripheral interface (SPI) module that supports the reading and writing of data to a SD memory card. This module can be connected to a microcontroller to record monitoring parameters. The SD card module in this data logger design has a 3.3VDC-regulated IC, operating voltage of 5 VDC and is equipped with a 4 GB micro SD card.

viii. **Real-Time Clock (RTC):** The RTC is an IC and battery module, which stores time and date information without receiving any external data. These data logger version uses the DS1307 RTC, I2C serial communication, 5VDC operating voltage and 3VDC internal battery.

ix. **Keypad module**: There are sixteen push-button contacts integrated into the 4X4 keypad, which are linked to the row and column lines. The microcontroller may detect a button-pressed status by scanning these lines. There are sixteen built-in push buttons spread over four rows and four columns in this keypad.

Mathematical modeling of the proposed monitoring circuit

Applying simple transformer formula,

$$S = \sqrt{3} * V * I \tag{1}$$

where S = Apparent power rating of the transformer; I = line current; V = phase voltage, S = 100 kVA, V = 220 V

$$I = \frac{S}{\sqrt{3}.V} = \frac{100 \text{ kva}}{3 * 220 \text{ v}} = 151 \text{ A} \tag{2}$$

Therefore, a current measurement sensor with capacity of 200 A is chosen.

Power supply unit

To prevent frequent power outages from preventing the system from recording data, a power supply circuit is designed as follows. The power supply unit consisted of two main paths;

Path 1: The power is supplied from the AC power supply (grid) via a 220/5V converter into a switching circuit and finally to the microcontroller.
Path 2: From AC supply to 220/5V converter to backup storage, from power supply to switching circuit and then to microcontroller.

These two supply paths are used independently. When mains power is available, path 1 will be in use, while path 2 will be in charge. The internal circuitry of the power bank automatically cuts off the power supply when the power bank is in charge mode. Therefore, when AC power is available, the Power Bank is charging and sending a zero output and the relay is not energized. The Power Bank will be in output mode as soon as the power supply is unavailable. The relay will automatically be energized and the contact will close in the direction of path 2. Figure 4 illustrates the layout of the power supply.

Power demand of the system.

Due to low output current value of the AC to DC converter, a single converter cannot simultaneously charge and supply the system. Hence, two independent converters

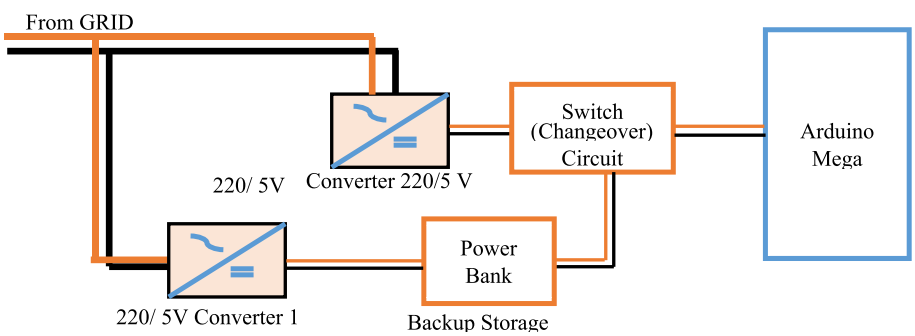

Fig. 4 Power supply topology

were selected for implementation. Table 1 shows the estimated backup energy needed to keep the system running for at most 3 days. The real-time clock (RTC) is powered by an internal battery. The battery can last up to 6 years. Even when the Arduino Mega microcontroller is turned off, the RTC keeps time. A power bank with a storage capacity of 10000mAh was used in the back path. In the changeover circuit, a relay was used and energized by the grid supply. Choosing a power bank with a capacity of 10000mAh, its autonomy can be obtained as Eq. (3) [34]:

$$\text{Power bank life} = \frac{\text{power bank capacity}}{\text{ESystem}} = \frac{10000\ \text{mAh}}{4050\ \text{mAh/d}} = 2.47\ \text{days} \tag{3}$$

If we used a 10,000mAh power bank, it would last for two and a half days. By observation, since the grid power cuts do not really last for more than two days in frequent cases, a 10,000mAh power bank was sufficient for the backup power supply for the system.

Fault detection algorithm

To complete this research several engineering tools such as simulation tools, coding tools and monitoring tools will be use. ThingSpeak is an online MATLAB data platform and application programming interface for the IoT that allows data to be stored and retrieved from devices over HTTP via a LAN or the Internet. Additionally, it can gather, store, analyze, visualize, and act upon data from other devices, including Arduino, and ESP32, as well as sensors and actuators. The Arduino IDE is a software platform for writing and uploading code to Arduino-compatible microcontroller boards. It offers a simple user interface for writing, compiling, and uploading code, enabling novice and skilled programmers to work with Arduino boards easily. Figure 5 is the flowchart that is used to illustrate the process carried out on the system. Starting from reading the sensors, the parameters of the transformer: load current, voltage, and power consumed by the load. Figure 6 flowchart illustrate ESP32 microcontroller updating the parameters of phase voltages and line currents to ThingSpeak server.

Table 1 Estimated backup energy

	Appliance	Quantity	Current (mA)	Operation time (h)	Energy consumed (mAh/d)
1	Microcontroller	1	20	24	480
2	Microcontroller (used pins)		200	8	1600
3	SD Card	1	30	20	600
4	Pzem-004t	3	20	15	900
5	ZMPT101B	1	2	15	30
6	LCD, RTC and Keypad	1	8.3	24	200
7	Esp32	1	10	24	240
Total energy consumed				4050	

Operating principle of microcontroller using logic table

Table 2 explained the combined operation of the distribution transformer remote monitoring and GSM-based reporting system.

Experimental setup

The experimental block is set up as in Fig. 7 using "Cirkit Designer software," which is a design software tool, is used for the simulation of this device. The proper design of the project hardware is tested through the software and physical simulation of the various blocks. The different blocks that make up the complete system assemble through a series of simulations and tests on the system to ensure that the system was theoretically good before venturing into implementation. Figure 8 shows the

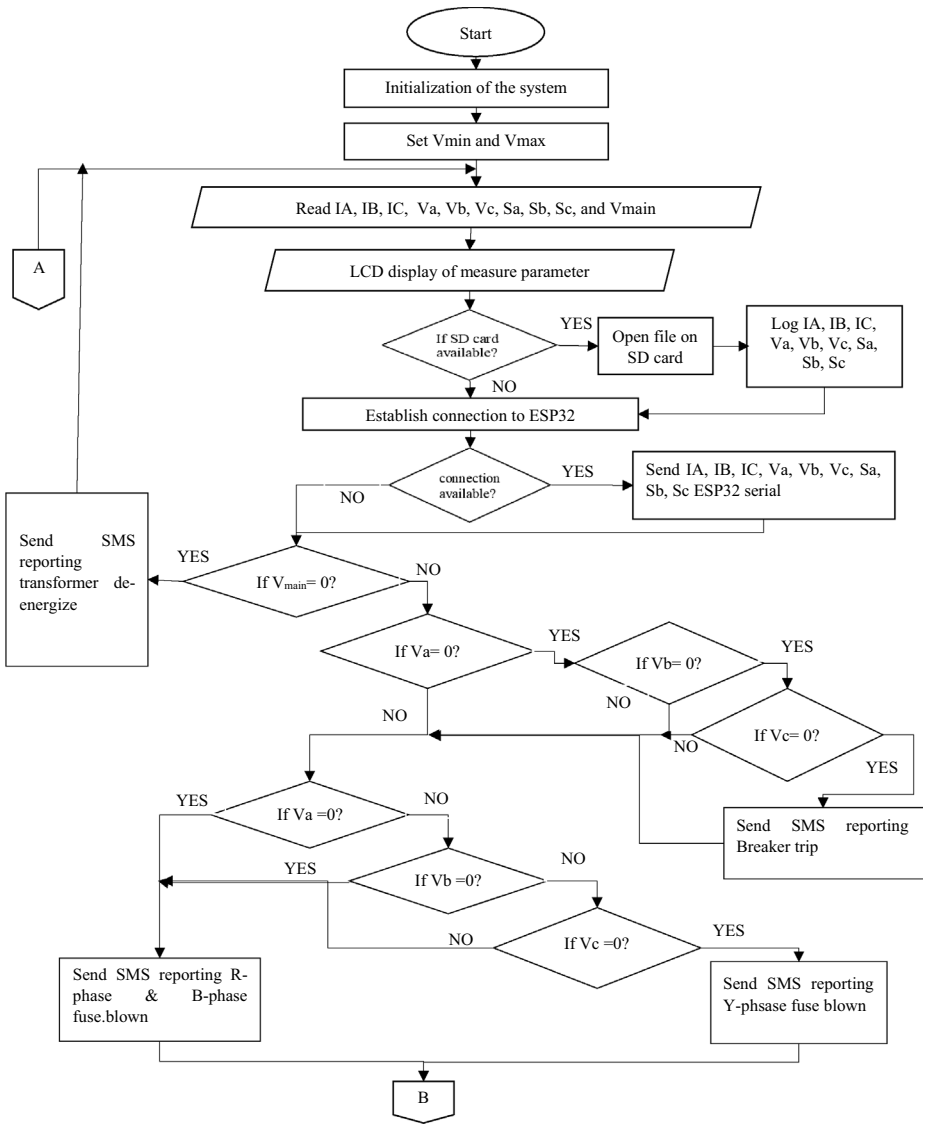

Fig. 5 Flowchart of Arduino base transformer monitoring, faults detection and reporting system

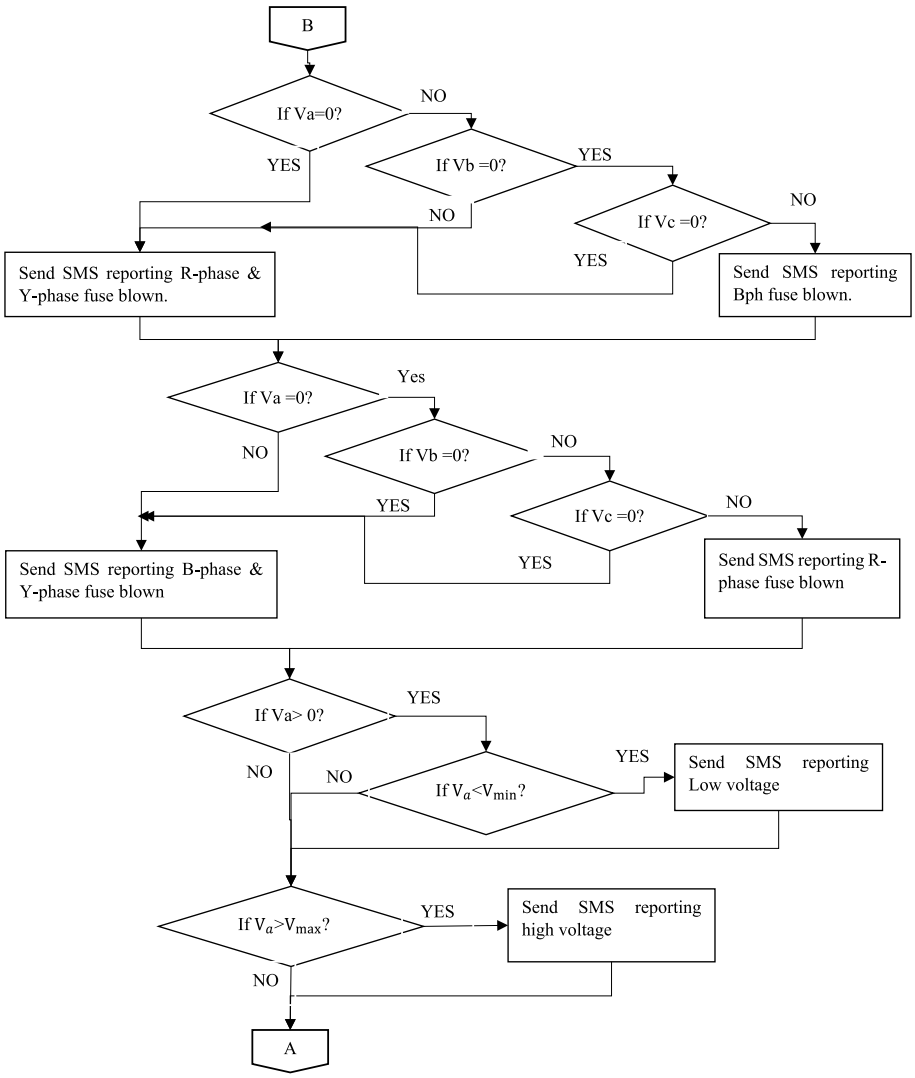

Fig. 5 continued

monitoring system's experimental setup connected to a 100 kVA 3-phase distribution transformer.

Pearson product–moment correlation

Pearson's correlation coefficient, sometimes referred to as Pearson's statistical test, is a measure of the closeness of a linear relationship between two variables. It measures how close a linear relationship is between two variables. The greater the linearity, the closer the coefficient is to + 1 or -1. A correlation of 0 means that there is no relationship. Equation (4) shows the relationship between the Pearson correlation coefficient.

$$r = \frac{\sum_{i=1}^{n}(x_i - \overline{x})\left(y_i - \overline{y}\right)}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}\left(y_i - \overline{y}\right)^2}} \tag{4}$$

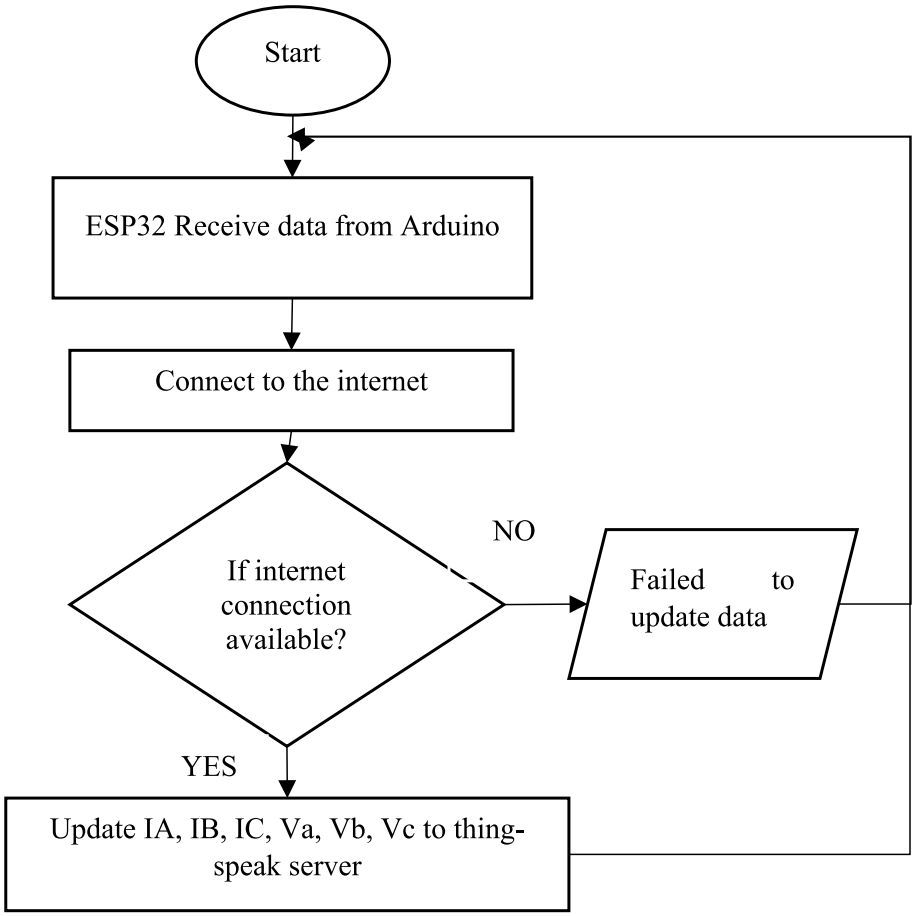

Fig. 6 Flow chart of ESP32 microcontroller updating the monitored parameter of voltage and current to ThingSpeak server

Table 2 Explanation of the role of the microcontroller using a logic table

Main Voltage sensor (V_{main})	PZEM-016 Voltage Phase1 (V_a)	PZEM-016 Voltage Phase2 (V_b)	PZEM-016 Voltage Phase3 (V_c)	Results	Comment
1	0	0	0	0	Breaker trip
1	0	0	1	0	Phase A and B Fuse blown
1	0	1	0	0	Phase A and C Fuse blown
1	0	1	1	0	Phase A Fuse blown
1	1	0	0	0	Phase B and C Fuse blown
1	1	0	1	0	Phase B Fuse blown
1	1	1	0	0	Phase C Fuse blown
1	1	1	1	1	Fuse is ACTIVE
0	-	-	-	0	Transformer de-energize

where r is the correlation coefficient, x is group 1 variables, y is group 2 variables, $\overline{x}$ is means of x, $\overline{y}$ is means of y, and n is a sample count.

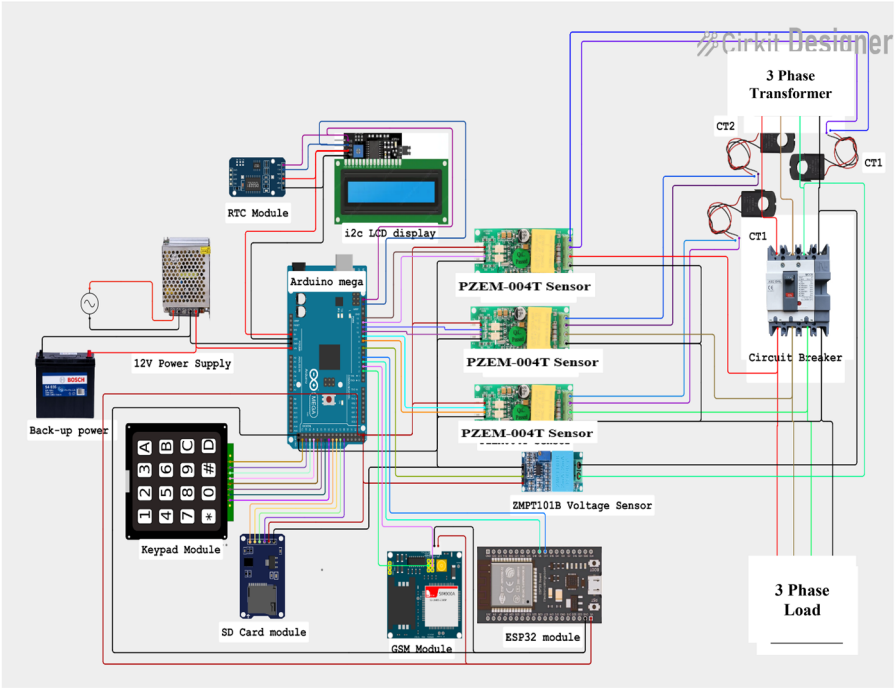

Fig. 7 Simulation of the monitoring and faults detection system on Cirkit designer

Fig. 8 Experimental setup of the monitoring system connected to a 3-phase supply at U-Block section (University of Bamenda)

The experiment involves an IoT-based monitoring device and a multimeter for measuring transformer voltage and current, with both connected to the secondary site distribution transformer. The recorded data is analyzed statistically to determine the agreement between the IoT and multimeter, as well as the system's accuracy and reliability, with the Pearson product–moment correlation coefficient quantifying the strength and direction of the linear relationship. Table 3 presents the performance interpretation of the Pearson correlation coefficient, as outlined by Roche et al. [35]. The analysis will also involve comparing the trends and patterns observed in the data from both instruments using Eq. (4).

Table 3 Performance rating by Pearson correlation coefficient

Pearson correlation coefficient (r)	Rating
0.91–0.99	Almost perfect
0.71–0.90	Too high
O.51–0.70	High
0.31–0.50	Moderate
0.11–0.30	Low
< 0.1	Too low

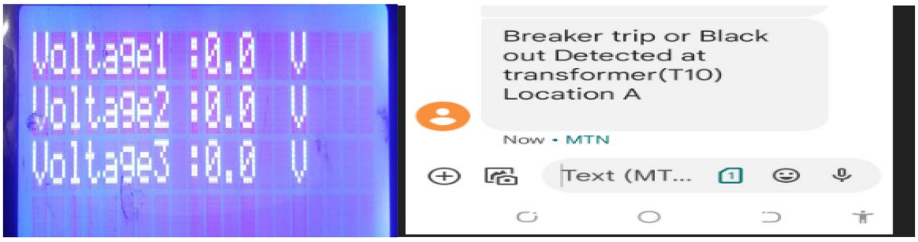

Fig. 9 Transformer trip or outage detection on transformer

The standard error (SE) of the Pearson correlation is calculated using Eq. (5)[36];

$$\mathrm{SE} = \frac{1 - r^2}{\sqrt{N - 3}} \tag{5}$$

where r is the correlation coefficient, N is the data size.

Results and discussion

The development of the IoT-based transformer monitoring and fault detection system provided important lessons about its performance and capabilities. A systematic approach ensured thorough testing and validation of each module by separating the system into hardware and software components. The ability of the system to detect failures, report conditions in real-time, and remotely monitor voltage and current parameters was thoroughly assessed, providing important insights. The results demonstrate the effectiveness of the system to achieve real-time monitoring, accurate fault detection and reliable reporting using IoT, which addresses key challenges of transformer maintenance and management.

Transformer trip or outage event detection and reporting

The system successfully detected in real time when the breaker was tripped or lost power. The PZEM sensors were able to detect a complete loss of power in all three phases. This triggered an immediate response. Upon detection, the microcontroller activated the GSM module to send a pre-programmed SMS message to the operator. The SMS message identifies the specific transformer and location of the fault. This capability significantly reduces downtime and improves system reliability by ensuring immediate

Voltage1 :289.7V
Voltage2 :240.9V
Voltage3 :235.4V
High Voltage fault Detected in Distribution Transformer at Location A(TO1),Urgent attention needed: Possible Neutral Failure
Now - MTN
Text (MT...

Fig. 10 Simulated high voltage detection on LCD

Fig. 11 Simulated blown fuse detection and reporting

action to isolate the faulty transformer and initiate repairs. Figure 9a shows the prototype's detection of a trip event, while Fig. 9b shows the corresponding SMS notification.

Transformer high voltage detection and reporting

The PZEM sensors accurately detected high voltage faults. These faults were often indicative of neutral failures or other anomalies. Phase one voltages were varied using an autotransformer and when the output voltage exceeded the set maximum threshold Vmax (250V), the system immediately displayed the fault on the LCD and alerted the operator via SMS. This feature enables timely intervention to prevent damage to the transformer and connected loads. The simulated high voltage results, shown in Fig. 10a, b, validate the system's ability to detect and report overvoltage conditions.

Blown fuse detection and reporting

The system's ability to detect and report blown fuses was effectively demonstrated during testing. The PZEM sensor continuously monitored the voltages across each phase, and any phase detected at zero voltage was flagged as a blown fuse if the next phase was different from zero. The microcontroller, indicating the affected phase and the location of the transformer, promptly initiated an SMS alert. Figure 11a, b shows the LCD and SMS notice for a simulated blown fuse condition, demonstrating the reliability of the system in dealing with this frequent problem.

Transformer low-voltage detection and reporting

Low-voltage condition was detected when the phase voltage was lowered by means of an autotransformer when the monitored voltage fell below the pre-set threshold of the minimum voltage level (198 V). The fault was displayed on the LCD and the operator was notified by SMS through the GSM technology as the system's response. This real-time

detection ensures rapid action for the stabilization of voltage levels and the maintenance of service quality.

Real-time data of current and voltage

One of the most powerful features of the system is its ability to provide real-time transformer voltage and current data. For accessibility in areas with limited internet connectivity, the monitoring data is transmitted to a centralized IoT platform (ThingSpeak server) and stored locally on an SD card. The concept of IoT was used in this project to send the measured data to the internet using the internet of things technology. ThingSpeak server was used to store the data, and the same can be collected. The platform updates data available on the server every 2 min by receiving new data and updating with the previous data, ensuring continuous data logging and real-time visualization of trends. This capability enhances load management, allowing operators to effectively balance loads across phases, especially when new loads are added, thereby

Fig. 12 Line current and the phase voltage viewed on ThingSpeak IoT server

Table 4 System Results for calculation Pearson's correlation coefficient

AC Voltage (V) on Va-phase		Current (A) on I_A-line	
(multimeter)	(device)	(multimeter)	(device)
AC voltage and current reading of Inverter			
216	215.95	16.4	16.876
215	214.46	15.4	15.079
218	217.81	15.1	15.482
215	215.17	13.5	13.263
216	215.64	16.7	16.416
214	213.69	14.4	14.776
216	215.83	14.9	15.193
217	215.94	12.8	13.216
214	213.39	12.2	12.597
216	215.91	13.8	13.502

Table 5 Pearson correlation results

Component	Pearson Correlation Coefficient (r)	Classification
The voltage reading of Va phase	0.96266	Almost perfect
The current reading of I_A-line	0.96898	Almost perfect

extending transformer life and improving system efficiency. Figure 12 shows real-time monitoring data on the ThingSpeak platform.

Figure 12 presents several curves depicting real-time data from the system. Curve (a) shows the load current on R-line, while curve (b) illustrates the load current on Y-line. Curve (c) represents the load current on B-line. Curve (d) indicates the voltage on R-phase, and curve (e) shows their voltage on Y-phase. Curve (f) displays the voltage on B-phase, respectively.

Monitoring these parameters provides a valuable understanding of the operation and behavior of the distribution transformer. It confirms with our objective to Access and track the real-time data on the secondary site of a distribution transformer via mobile networks to the ThingSpeak server.

The Pearson correlation coefficient was used to verify the readings from the monitoring device and a multimeter. The correlation between the IoT monitoring device and a multimeter was determined. Multiple readings were collected every two minutes using a multimeter, and the average was taken, as shown in Table 4. The Pearson's correlation results are then presented in Table 5 after the calculation using Eq. (4).

Assumption: The current and voltage monitoring sensors across the three phases are the same (PZEM-004t), so we assume the measurement accuracy on the R phase is same as ON the other phases.

Overall, the Pearson correlation coefficient from our calculation suggests a strong relationship between the monitoring device and the multimeter.

From Eq. (5),

$$SE = \frac{1 - 0.96266^2}{\sqrt{50 - 3}} = 0.0107$$

At a 95% confidence level (Z = 1.96) [37], the margin of Error (MoE) is:

$$\text{MoE} = \text{Z} \times \text{SE} = 1.96 \times 0.0107 \approx 2.1\%$$

Therefore, the system's monitoring and fault detection accuracy is (96.266% ± 2.1%) at a 95% confidence level.

Discussion

The system demonstrated high reliability in the detection of transformer faults, including fuse failures, neutral failures and tripping events. Each fault condition was accurately identified and immediately reported to the operator by means of GSM-based short message service notifications. The results are consistent with previous studies, such as that of Okafor et al. [17], which demonstrated GSM-based systems for real-time fault reporting but failed to provide robust phase-specific fault detection. The ability of the implemented system to identify specific fault types improves response efficiency and reduces downtime. The proposed system successfully detects overvoltages when the voltage read by the sensor is above the set maximum voltage (250V) and undervoltages when the voltage falls below the set minimum voltage (198V), and displays fault alerts on an LCD and then sends SMS alerts notifying the network operator of the detected fault. Figures 10 and 11 illustrate the system's ability to handle these anomalies effectively. The results are consistent with previous work, such as that of Hanafi [19], but provide improved reporting accuracy by integrating IoT capabilities for remote monitoring.

The real-time voltage and current monitoring of the system, enabled by PZEM 004t sensors, ensured a high level of accuracy. The data logger utilizes a microcontroller-based design and local storage media, ensuring reliable and cost-effective data recording. The stored data can be retrieved and analyzed offline, providing valuable insights into the long-term performance and trends of the distribution transformer. The data are logged locally on an SD card and transmitted to the IoT platform, allowing operators to analyze phase imbalance and identify overload trends on the transformer. The alert system is integrated with the real-time monitoring capabilities, allowing for rapid detection and response to potential problems. This feature reflects findings by Provči et al. [38], who noted that instant fault detection reduces downtime and operational costs associated with manual monitoring. The performance of the system can be observed with the help of this device with an internet connection to log the monitored data into the ThingSpeak server as demonstrated in Fig. 12 which is consistent with the research conducted by Kumar et al. [39]. These results extend previous work by Subha et al. [29], emphasizing the integration of IoT for improved accessibility.

A multimeters was used to measure the real-time data as demonstrated in Table 4, which provides a Pearson correlation comparison between the monitoring device and standard multimeter readings for voltage and current measurements across the secondary site of a 100 kVA distribution transformer. The correlation between the two devices was carried out using the Pearson correlation coefficient and the standard error relation in Eq. (4) and (5), respectively, the results are demonstrated in Table 5. The device

accuracy is validated by a Pearson correlation coefficient outcomes exceeding 0.96 when benchmarked against the industrial-standard of acceptable range 0.8 as illustrated by Rocha et al. [35], Ningsih et al. [40] and Li et al. [41]. With classifications such as "almost perfect." The high correlation suggests a very strong positive linear relationship between the proposed monitoring device and the multimeter supported by Rocha et al. [35], and Azzawi et al. [42] indicating that the two devices are closely related validity that the IoT monitoring device is a reliable, accurate instrument and device's ability to capture real-time data. The proposed system offers a number of advantages in comparison with traditional manual monitoring systems. Its automated detection reduces human error and response times, while its real-time data display enhances decision-making. The proposed approach improves the efficiency of the electricity distribution network by using IoT and GSM technologies to enable automatic fault detection and real-time monitoring. It quickly identifies problems such as neutral failure, overvoltage and fuse failure, and notifies operators immediately. The predictive maintenance approach improves decision-making and load balancing, eliminating manual checks with an affordable, scalable, and reliable approach suitable for both urban and rural power grids.

Expected maintenance frequency and operational challenges

The proposed IoT monitoring system is designed to be low-maintenance. Its components are generally durable and the need for routine recalibration or replacement is minimal, such as the microcontroller, data logger and sensors. Depending on environmental conditions such as dust or moisture that can affect the accuracy of the sensors, the sensors needs to be recalibrated or replaced approximately every 4 to 6 years. The primary operational challenge is maintaining a consistent Internet connection for real-time data transmission. While the device includes offline data storage for SD cards to reduce data loss in the event of connection problems, continuous remote monitoring and alerting depend on stable network coverage. Despite its strengths, the system's reliance on GSM for communication poses challenges in areas with poor network coverage, alternative connectivity options, such as LPWAN or satellite Internet, may need to be considered to maintain operational effectiveness even though it comes with extra cost.

Conclusion

This research presents an innovative, real-time monitoring and fault detection system specifically designed for 100 kVA distribution transformers. It employs IoT-driven data visualization through ThingSpeak, GSM-based SMS notifications, and sophisticated sensing technologies to ensure precise fault detection and effective remote monitoring. The system has shown a strong correlation with standard measuring instruments (Pearson's $r > 0.96$), confirming its accuracy and reliability. It successfully identified and communicated critical issues such as blown fuses, transformer tripping, neutral failures, as well as overvoltage and undervoltage events. Real-time data logging, along with cloud updates, functioned well under diverse operating conditions. By automating fault detection and notifications, the system minimizes downtime, supports predictive maintenance, and enhances utility operators' decision-making. These enhancements address significant shortcomings in conventional transformer monitoring systems, which typically depend on manual inspections and experience

delays in fault identification, thereby improving operational efficiency and reliability in both urban and rural power networks. Additionally, the system offers a scalable and cost-effective alternative to manual monitoring methods. However, there are certain limitations. The system is tested only on a 100 kVA transformer and may not be fully applicable to transformers with higher capacities, and it currently does not include parameters like oil level or temperature readings, which are also a cause of transformer failures. Its performance may also be constrained by GSM connectivity, which could impede its functionality in regions with poor network reception. Environmental factors and sensor degradation over time could impact long-term precision. By lowering transformer failure rates, optimizing load distribution, and enabling remote fault resolution, this system lessens the necessity for emergency generator use and frequent maintenance visits. This actively supports SDGs by indirectly reducing CO_2 emissions tied to energy distribution and transportation.

To further enhance this work, future systems should cater to larger-capacity transformers and integrate additional diagnostic parameters such as temperature, oil level and vibration monitoring. Improving communication reliability to address GSM-related challenges through alternative technologies like LoRaWAN or satellite connections, and incorporating AI-driven predictive analytics, would allow for the forecasting of transformer faults prior to failure, thereby reducing repair expenses and energy losses, and significantly bolstering the system's scalability and functionality in smart grid settings.

Abbreviations

CO_2	Carbon dioxide
GSM	Global System for Mobile Communications
I_A	R-Line current
I_B	B-Line current
I_C	Y-Line current
IoT	Internet of Things
kVA	Kilovolt Ampere
LPWAN	Low Power Wide Area Network
r	Pearson's correlation coefficient
S	Apparent power
SD	Secure digital
SE	Standard error
SDGs	Sustainable Development Goals
SMS	Short message service
V_a	R-phase voltage
V_b	B-phase voltage
V_c	Y-phase voltage
V_{max}	Maximum set voltage
V_{main}	Main voltage reading
V_{min}	Minimum set voltage

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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